

Modeling the impact of global warming on water temperature and seasonal mixing regimes in small temperate lakes

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Global warming increases the vertical stability in small lakes and makes a future transition between different mixing regimes possible. In order to estimate this effect, the one-dimensional lake temperature model, FLake, is applied to two lakes located in Berlin, Germany, that have similar morphometrical characteristics but that differ in the mixing regime. The model is driven by long-term meteorological data and by regional climate scenarios. The current rate of increase in the year-round lake temperature of 0.3 °C per decade is found to coincide with the trend in the air temperature. The warming rates are unevenly redistributed over the seasons and across the water column; the strongest warming occurs in winter and slight cooling of the near-bottom waters occurs in summer. In future scenarios, both lakes change their mixing regime to warm monomictic over the course of the century. Successive transitions between poly-, di- and monomictic states reveal themselves through a series of abrupt changes in the near-bottom temperature during summer, which can significantly affect the water–sediment nutrient exchange and the benthic biological communities.

Introduction

Quasi-enclosed small lake ecosystems are advantageous for the investigation of climate-driven changes because they provide a clear separation between the external climatic forcing and the interactions inside the system. Most of the external forcing comes from the surface of the lake by means of energy and matter exchange with the atmosphere. As a result, the physical characteristics of a lake (such as temperature distribution and mixing intensity) first react to climatic trends in the atmosphere and determine to a large degree all subsequent changes of the chemical and biological components of the ecosystem. Therefore, many recent studies that

examine the responses of lakes to climate change focus on estimating the long-term changes in the lake temperature and the mixing regime (e.g., De Stasio *et al.* 1996, Fang and Stefan 1999, Blenckner *et al.* 2002, Peeters *et al.* 2002, Danis *et al.* 2004). Another advantage of using lakes as indicators of climate change lies in the fact that the majority of them are small enough to exclude horizontal inhomogeneities from consideration, which allows the problem to be reduced to the investigation of the vertical mass and energy transport in a water column. When attention is confined to the physical characteristics of the lake, the one-dimensional model is a convenient method for the study of heat transport in the lake–atmosphere system at seasonal to cli-

matic time scales. Methods that model the one-dimensional lake temperature are well developed and many are used as basic research tools in the aforementioned studies.

One important aspect of the impact of global warming on lakes, as reported by previous studies, consists of the anticipated increase in the vertical stratification during summer (Elo *et al.* 1998, Hostetler and Small 1999, Livingstone 2003). According to Hutchinson's (1957) classification, the majority of mid-latitude lakes belong to two different seasonal-mixing types: polymictic (i.e., mixed down to the bottom several times during the summer heating period) and dimictic (i.e., continuously stratified between the spring and autumn overturns). The climate-driven increase in the summer stability can potentially result in turning a certain class of polymictic lakes to dimictic conditions. Such a change in the mixing regime can affect all components of a lake's ecosystem. Therefore, a comparison of the responses of a dimictic and a polymictic lake to climate change and an estimation of the probability of a polymictic/dimictic regime transition would significantly contribute to the understanding of the long-term response of lake ecosystems to global warming.

The aims of the present study are:

1. To estimate the observed and expected changes in the temperature and mixing regimes of central European lakes with a focus on the shallow lakes, which are the largest lake group in the region. The interest in the European lakes is due to the importance of the quality of the lake water for the well-populated region. The lakes undergo intensive local anthropogenic impact that cannot be estimated without knowledge of the climatic background.
2. To compare the responses to climate change of two major classes of temperate lakes: dimictic and polymictic. As mentioned above, the climate-driven increase in the vertical temperature stratification in the lakes suggests a possible transition from a polymictic to a dimictic regime in certain shallow lakes. This possibility is estimated below.
3. At the same time, current observations

indicate that the regional warming trends in Europe are unevenly redistributed over the seasonal cycle with larger temperature increases taking place in winter (Parker *et al.* 1994, Paeth *et al.* 1999, Volodin and Galin 1999, Livingstone 2003). The response of the lake mixing regime to this asymmetry is another question for this study.

The lake temperature model, FLake (Mironov 2008), is used in the subsequent analysis together with long-term observational data from two lakes located in Berlin, Germany, and regional climate scenarios for the end of the 21st century, which have been developed at the Potsdam Institute for Climate Research PIK and at the Rossby Center, Sweden. A description of the study sites, data sets and scenarios together with a short model description and the validation results are presented in the next section. Thereafter, simulation results for the long-term temperature dynamics in the two lakes for the periods of 1961 to 2002, 2005 to 2055 and 2071 to 2100 are presented. In the following discussion, typical future scenarios for the transition of the mixing regimes in the shallow lakes in the region are derived based on the modeling results. Some ecological implications of the results are outlined in the concluding remarks.

Material and methods

Study sites: Müggelsee and Heiligensee

Two shallow lakes located in Berlin, Germany, were chosen as modeling objects and data sites for this study: Müggelsee and Heiligensee. Several features of the two lakes are the reasons why these lakes had been chosen. First, both lakes are situated in a densely-populated area, which makes the investigation socially important and provides relatively easy long-term ecological monitoring. Since such monitoring had been performed during the last decades, a time series of various lake parameters is available for the period of 1979 to the present for Müggelsee and for the period of 1975 to 1992 for Heiligensee. Second, both lakes have very similar morphometry (Table 1). In addition, the atmospheric forc-

ing is virtually identical because the lakes are located very close to each other.

However, Müggelsee is polymictic, i.e., mixed down to the bottom several times during the summer heating period, and Heiligensee is dimictic, i.e., continuously stratified between the spring and autumn overturns. This fact provides the opportunity to estimate the climatic response of the two most common temperate lake types under virtually the same climatic forcing.

The inflow and outflow play a certain role in the dynamics of Müggelsee, which belongs to the River Spree system. The Spree throughflow provides intensive water exchange with a theoretical retention time of about 42 days. Nevertheless, it has been found that the throughflow only has a minor impact on the vertical thermal structure of the lake; the river water mainly follows the lake surface and poorly mixes with the denser lake water (Kirillin 2002). Heiligensee, in turn, has no significant in- and outflows; the lake is only connected to the Havel River by a small one-to-two-meter deep canal. Therefore, the impact of the inflow is excluded from further analysis. Additional details on the physical and biological regimes of both lakes can be found in Driescher *et al.* (1993) and Adrian *et al.* (1995).

Global warming scenarios

Three input data sources are used for the model input: a long-term meteorological data set for the period of 1961 to 2002 that is provided by the German Weather Service (DWD) and two regional climate scenarios for the periods of 2005 to 2055 and 2071 to 2100. The 1961–2002 data set covers standard meteorological observations at the Potsdam meteorological station, which is located about 20 km from both lakes.

The regional climate scenario, which has been developed at the Potsdam Institute of Climate Research (PIK) for the Elbe River area, is used to predict the atmospheric forcing on the lake in the near future (Jacob and Gerstengarbe 2005). The scenario, which provides daily values of the main meteorological characteristics for the period of 2005 to 2055, is achieved by the method of regional statistical downscaling, which uses mean climatic trends that are based

on the global atmosphere-ocean circulation model (GCM) ECHAM4/OPYC3 (Roeckner *et al.* 1999) and the International Panel on Climate Change (IPCC) greenhouse emission scenarios (Watson 2001).

The regional climate scenario for the period of 2071 to 2100 is adopted from the PRUDENCE data archive (<http://prudence.dmi.dk/>). The MPIB2 scenario was chosen (Räisänen *et al.* 2004), based on the ECHAM4/OPYC3 global circulation model with the IPCC SRES B2 emission scenario (Nakićenović and Swart 2000, Watson 2001), which corresponds to moderate emission of greenhouse gases in the future. The choice is conditioned by several considerations. First, in contrast to the scenarios based on the HadAM3H global circulation model, the MPIB2 scenario predicts that the strongest regional warming will take place in winter, which is consistent with the seasonal warming pattern that was observed during the period of 1961 to 2002. Second, general warming trends, which are provided by the B2 emission scenario, are also close to those observed during the last 40 years. In this sense, the MPIB2 scenario can be considered as future modeling of the “if the current warming tendency persists” case. Third, the MPIB2 scenario differs from the GLOWA Elbe scenario for the period of 2005 to 2055 only by the regional downscaling procedure (dynamical downscaling in the first case and statistical downscaling in the second) but involves the same greenhouse emission scenario and the same global climate model (ECHAM4/OPYC3). This allows them to be considered to the first approximation as two subsequent time series from the same climatic scenario. Together with the long-term meteorological observations over the last 40 years, they comprise an input set that allows the estimation of climate-driven changes in the lake on a time scale that spans a century and a half.

Table 1. Geographical and morphometrical characteristics of the study sites.

Lake	Location	Depth (m)		Area (km ²)
		Mean	Max.	
Müggelsee	52°26'N, 13°39'E	4.9	8.0	7.3
Heiligensee	52°36'N, 13°13'E	5.9	9.5	0.3

Three long-term model runs were performed based on the three inputs described above: 1961–2002 with meteorology observation data provided by the German Weather Service as input, 2005–2055 with external forcing from the GLOWA climate scenario, and 2071–2100 forced by the RCAO MPIB2 climate scenario. The model output consists of daily values of the upper mixed-layer temperature, T_s ; the mixed-layer depth, h ; and the temperature jump across the stratified layer, ΔT .

Lake temperature model FLake

The thermal regime of the lakes is calculated with the help of the lake temperature model, FLake (Mironov 2008, *see also* Mironov *et al.* 2010). FLake is a one-dimensional model that is based on a two-layer parametric representation of the vertical temperature structure. The upper layer is treated as well-mixed and vertically homogeneous. The structure of the lower stably-stratified layer, the lake thermocline, is parameterized using a polynomial self-similar representation of the temperature profile. The depth of the mixed layer is computed from the prognostic entrainment equation in convective conditions, and from the diagnostic equilibrium boundary-layer depth formulation in conditions of wind mixing against the stabilizing surface buoyancy flux.

For the one-dimensional (1-D) case, the problem of modeling the temperature and mixing evolution reduces to finding the solution to the 1-D vertical heat transfer equation,

$$\frac{\partial T(t, z)}{\partial t} = -\frac{\partial Q(t, z)}{\partial z}, \quad (1)$$

where T is the horizontally averaged lake temperature, Q is the horizontally averaged vertical temperature flux, t is the time and z is the vertical coordinate. The basic principle underlying the model consists of splitting the water column into horizontal layers, by means of physically-motivated assumptions about their properties, that allows subsequent integration of the governing equations over these layers. By that means, the thickness of the layers together with their thermal characteristics become the prognostic variables. In this sense, FLake belongs to the family of bulk-

models that are also called layered, integrated, or lagrangian (Imberger and Patterson 1981). The last name expresses the ability of the model to calculate the vertical displacement of the layers with fixed properties instead of the change in the properties at fixed points across the water column (the so-called Eulerian approach). Mixed-layer models of surface boundary layers in the ocean, in the atmosphere and in lakes are the most famous examples of the bulk modeling approach. Niiler and Kraus (1977) present an extended discussion of the bulk-modeling principles and a comparison against local closure models, which are based on the solution of Eq. 1 at discrete points in the water column. In comparison with the other models, the main distinction of the present model is the application of the “thermocline self-similarity” hypothesis to represent the lower stratified layer. The idea was put forward in the early seventies by Kitaigorodski and Miropolsky (1970) and consists of adopting the thermocline thickness, $\Delta h(t)$, and the temperature jump across the thermocline, $\Delta T(t)$, as universal scales for the temperature profile, $T(t, z)$ (Fig. 1). In this case, the dimensionless temperature, ϑ , and the dimensionless vertical coordinate, ζ , can be introduced as

$$\vartheta = \frac{T(t, z) - T_s(t)}{\Delta T(t)}, \quad \zeta = \frac{z - h(t)}{\Delta h(t)}, \quad (2)$$

where T_s is the temperature in the mixed layer and h is the mixed-layer depth.

The self-similarity of the temperature profile implies universality of the function $\vartheta(\zeta)$ for all lakes. An analytical expression for the self-similarity function, $\vartheta(\zeta)$, can be derived by grouping together dimensionless temperature profiles from a number of lakes and by fitting them with a polynomial or other analytical function. Several expressions for the $\vartheta(\zeta)$ that all represent a similar thermocline shape have been proposed by various authors. A comprehensive review of the various self-similarity representations of the thermocline is presented by Kirillin (2002). Based on Eq. 2, the vertical temperature profile across the entire water column can be represented as follows (Fig. 1):

$$T(t, z) = \begin{cases} T_s(t) & \text{at } 0 \leq z \leq h(t) \\ T_s(t) - \vartheta(\zeta) \Delta T(t) & \text{at } h(t) \leq z \leq h(t) + \Delta h(t) \end{cases} \quad (3)$$

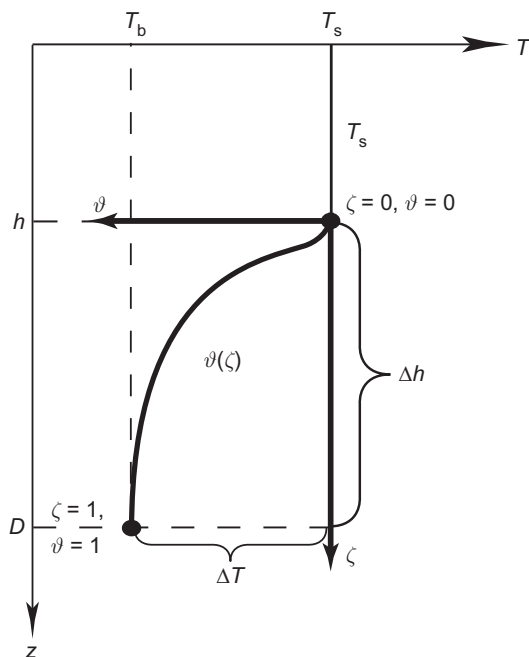


Fig. 1. Definition of scales used in the self-similarity representation of the lake thermocline (see text for notation).

Substituting Eq. 3 into Eq. 1 and subsequently integrating across the layers $0 < z < h$ and $h < z < (h + \Delta h)$ allows the partial differential Eq. 1 for $T(t, z)$ to be rewritten in the form of two ordinary differential equations (ODE's) for $T_s(t)$ and $\Delta T(t)$ [or $T_b = T_s(t) - \Delta T(t)$]. Integration of the turbulent kinetic energy (TKE) equation across the upper mixed-layer (Nüiler and Kraus 1977), results in an ODE for the evolution of the mixed-layer depth, $h(t)$. The derivation procedure and the exact ODE expressions can be found in Mironov (2008, see also Mironov *et al.* 2010). The solution of the initial-value problem for the set of three ODE's is performed using the simple Newton method with a constant time step. The boundary conditions on the z -coordinate enter the reformulated problem as the time-dependent functions for the surface and bottom heat fluxes (Q_s and Q_b , respectively) and the surface momentum flux, τ_s ; the latter is used in the TKE equation for estimating the impact of the wind-generated mixing on the mixed-layer $h(t)$ evolution. A separate model block calculates the surface heat and momentum fluxes from the standard meteorological variables and from the water surface temperature at the previous time

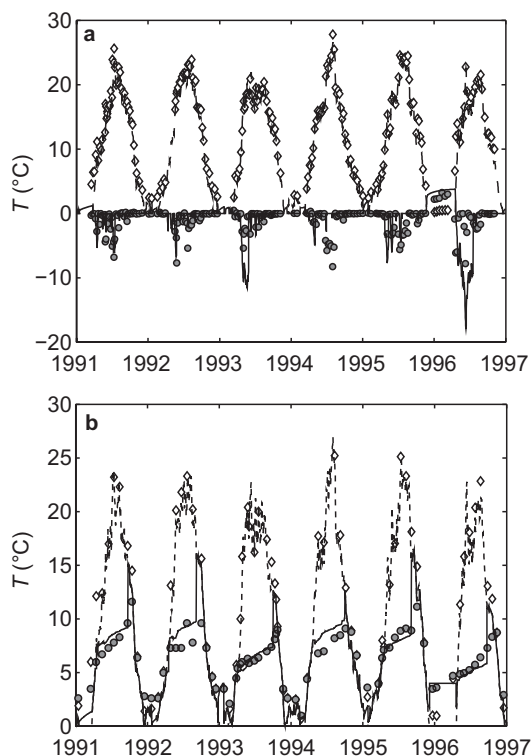


Fig. 2. Modeled vs. measured temperature evolution during 1991–1997 in (a) Müggelsee and (b) Heiligensee. Solid line and open diamonds in both panels represent the modeled and measured temperature at the lake surface, respectively. Dashed line and filled circles in panel a show modeled and measured surface-bottom temperature differences, respectively; dashed line and filled circles in panel b stand for the modeled and measured bottom temperature.

step based on the Mironov *et al.* (1991) algorithm. The short-wave solar radiation is calculated internally using the one-band exponential law for radiation decay in the upper water column. The FLake model has also been supplemented with a module to compute the ice thickness and its time evolution (Mironov and Ritter 2003). A model of the temperature evolution in sediments (S. Golosov and G. Kirillin unpubl. data) is integrated with FLake to calculate the bottom heat flux, Q_b .

The solution procedure consists of estimation of the mixed-layer depth, h , its temperature, T_s , and the temperature difference across the thermocline, ΔT , at each time step. If the calculated value of h is equal to or larger than the mean lake depth, D , the lake is supposed to be fully mixed vertically with $\Delta h = 0$ and $\Delta T = 0$ (Fig. 2). If

the mixed-layer temperature, T_s , drops to zero, two additional variables, the ice thickness and temperature, are calculated in the ice block of the model. A time step of one day with a corresponding averaged meteorological input is used in all model calculations below.

Model validation

The model validation is performed using the 1985 to 1997 temperature data for Müggelsee and Heiligensee. The model demonstrates good performance in simulating both the temperatures and the mixed-layer depth in both lakes (Fig. 2). In each case, polymictic and dimictic behavior of the lake is adequately reproduced. Only under the same atmospheric forcing, there are three model input variables that determine the mixing regime of the lake: mean depth, wind fetch (taken as the square root of the lake area) and the water transparency (the light extinction coefficient). Heiligensee is only 1 m deeper than Müggelsee but has, essentially, a smaller surface area. However, increasing the wind fetch for Heiligensee to that of Müggelsee has no appreciable effect on the modeled mixing regime. The data on light extinction is scarce, especially for Heiligensee, and suggests slightly higher water turbidity in Heiligensee. Constant mean values of 1.2 m^{-1} and 1.7 m^{-1} are adopted in the model for Müggelsee and Heiligensee, respectively. The sensitivity model runs reveal that reducing the light extinction coefficient in Heiligensee to about $1.0\text{--}1.2 \text{ m}^{-1}$ occasionally results in destruction of the summer stratification. This noteworthy result suggests that the water turbidity has a crucial role in supporting the dimictic regime of the lake and demonstrates the possible backward effect of the biology of the lake on the thermal regime.

The interannual variations in the temperature and mixing are also fairly reproduced by the model. The remaining uncertainty can be ascribed to the seasonal variations of the transparency, which are strong in both lakes, but cannot be reproduced in the model. Although existing information regarding the extinction variability in Müggelsee should allow derivation of an approximation for the seasonal course of the extinction coefficient, the data from Heili-

gensee is insufficient for it. Moreover, there is no guarantee that such an approximation would remain valid for future climate scenarios. Therefore, in this study, the extinction coefficients are kept constant throughout long-term calculations to ensure that all of the modeled changes in the temperature and mixing regime are caused only by atmospheric input variability.

Overall, the results of the verification are evidence of the ability of one-dimensional models to simulate the seasonal temperature and mixing cycle in lakes, as demonstrated in previous studies (e.g., Hondzo and Stefan 1993, Blenckner *et al.* 2002, Danis *et al.* 2004, Coats *et al.* 2006).

Results

External forcing

External forcing enters the model through the incoming solar radiation, I_0 , and the heat exchange at the surface of the lake, Q_s . The net short-wave solar radiation input remains nearly constant during the observational period of 1961 to 2002 (except for the weak, statistically-insignificant decrease, *see* below) as well as in the regional climatic scenarios. The heat flux at the surface of the lake is due to heat exchange between the air and water, heat losses due to evaporation and long-wave radiative fluxes from the atmosphere and from the lake. These flux components were calculated in the model by using the algorithm described by Mironov *et al.* (1991), which is based on the modeled surface temperature of the water and the meteorological variables (air temperature, air humidity, wind force and cloud amount) that are provided by the standard meteorological observations or regional climate scenarios. Long-term changes in the observed meteorological forcing during the period of 1961 to 2002 were estimated using a linear trend analysis. In order to reduce the effect of autocorrelation inside the data series on the significance of the calculated trends (von Storch 1999), the data was annually averaged before estimating the trends. The linear slope, a , was found by minimizing the squared differences between the observed series, $x(t)$, and the linear regression line, $\hat{x} = at + b$, where t is the

time. The standard error, S_a , of the estimation is defined as (Wilks 1995):

$$S_a = \frac{1}{\sqrt{n-2}} \frac{\sqrt{\sum_{i=1}^n [x(t) - \hat{x}(t)]^2}}{\sqrt{\sum_{i=1}^n (t - \bar{t})^2}}, \quad (4)$$

where n is the length of the data set. In order to further increase the statistical significance of the trend estimation, the length of the time series, n , is replaced by the “effective length”, n_e , defined as (Wilks 1995):

$$n_e = n \frac{1-r}{1+r}, \quad (5)$$

where r is the first lag autocorrelation coefficient. Trend significances were estimated by computing Student’s t scores as $t = a/S_a$, and by calculating p values for these scores for $n_e - 2$ degrees of freedom.

The most pronounced trend in the meteorological observations over the past 40 years exists in the air temperature, T_a , (Table 2). It amounts to a significant increase of about 0.29 °C per decade. There is also a tendency for the cloud amount to significantly decrease by about 0.8% per decade. A slight (statistically non-significant) increase in the short-wave solar radiation is apparently conditioned by the lower amount of clouds. Both the wind speed and the air humidity reveal no statistically significant trends.

The GLOWA regional climate scenario for 2005–2055 is based on the prescribed linear temperature trend of a 1.4 °C increase per 50 years or a 0.257 °C increase per decade, which has been adopted from the results of the global circulation model ECHAM/OPYC3 (Jacob and

Gerstengarbe 2005). The statistical properties of the other characteristics are derived from the long-term observational data by the statistical downscaling procedure. Therefore, the statistical properties are essentially the same as the observations from 1961 to 2002. The air-temperature increase in the RCAO MPIB2 scenario for 2071 to 2100 is also based on the ECHAM/OPYC3 results of the global circulation modeling and roughly amounts to a 0.3 °C increase per decade. No significant trends are present in other data series. Since the statistical properties of the variables in the regional climatic scenarios are either prescribed *a priori*, as in the statistical downscaling for GLOWA, or are produced by numerical modeling, as in dynamical downscaling for RCAO MPIB2, the trend significance analysis is irrelevant to them and not provided here.

Apart from the annual mean trends in air temperature, the seasonal distribution of warming is of critical importance for the response of the lake. A comparison of the mean seasonal course of air temperatures during 1961–1970 and 1991–2000 (Fig. 3a) demonstrates that the strongest warming takes place in the winter and spring months, which has also been reported in several previous studies on regional climate change in central Europe (Parker *et al.* 1994, Volodin and Galin 1999, Livingstone 2003, Luterbacher *et al.* 2004). The mean seasonal course of T_a from 2021 to 2030 is revealed by the GLOWA-scenario to have an equally distributed warming trend over the seasons whereas the RCAO MPIB2 scenario (the curve for 2081–2090 in Fig. 3b) reproduces stronger warming in winter-spring, which is similar to the present situation.

Table 2. Long-term (1961–2002) trends in the meteorological variables measured at the Potsdam station and those derived from the regional climate scenarios GLOWA (2005–2055) and RCAO MPIB2 (2071–2100). Values set in boldface are considered significant.

Variable (unit)	1961–2002				2005–2055	2071–2100
	Trend slope (a)	$t = a/S_a$	$n_e - 2$	p	Trend slope (a)	Trend slope (a)
Solar radiation (W m ⁻²)	0.1029	1.47	59	0.07	0.1288	–0.0213
Air temperature (°C)	0.0289	2.38	44	0.01	0.0257	0.0301
Rel. humidity (%)	–0.05	0.87	48	0.19	–0.10	0.01
Wind force (m s ⁻¹)	–0.0107	1.45	50	0.08	–0.0009	0.0003
Cloudiness (%)	–0.08	1.89	76	0.03	–0.09	–0.02

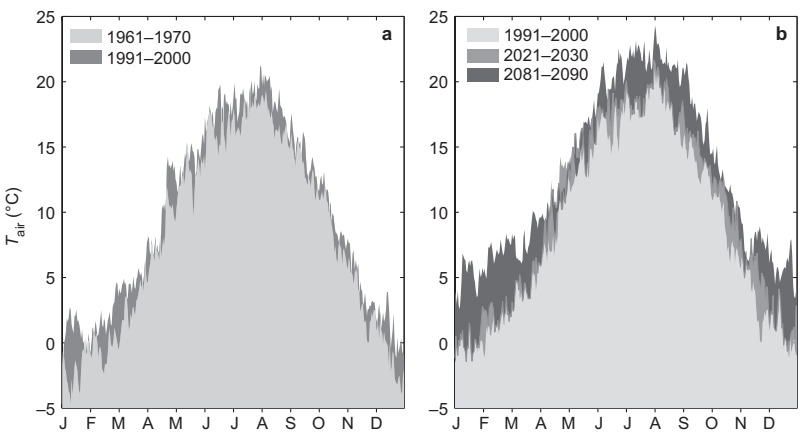


Fig. 3. Seasonal course of the air temperature averaged over decades. (a) Observations at the Potsdam meteorological station, the 1990s vs. 1960s. (b) Climatic scenarios vs. the 1990s.

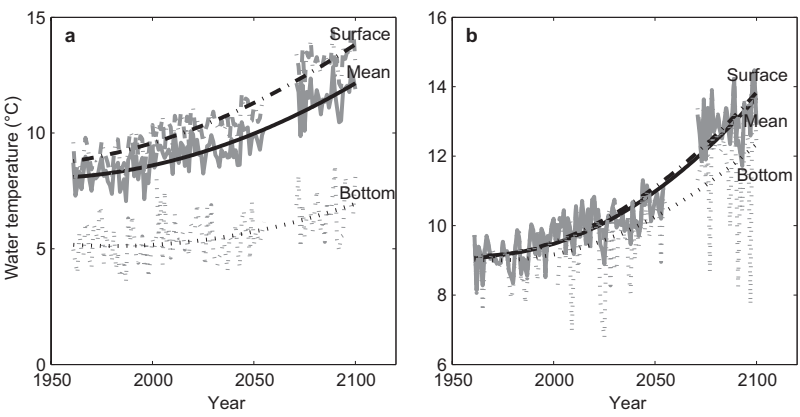


Fig. 4. Modeled surface (dash-dotted line), bottom (dashed line) and lake-averaged (solid line) water temperatures in Heiligensee and in Müggelsee. Gray lines are the annual means, black lines are the second degree polynomial fits.

Mean water temperature trends and changes in the seasonal mixing pattern

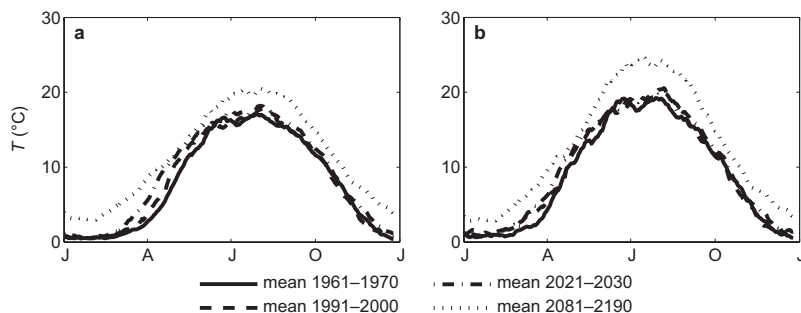
The annual mean temperature that has been modeled for the period of 1961 to 2100 reveals similar warming trends — an increase of about 0.3 °C per decade — in both lakes, which is close to the trend in the air temperature (cf. Table 2). The result is not surprising because both lakes are shallow and their annual mean heat exchange with the atmosphere is close to

zero. However, the redistribution of warming between the upper and lower layers of the lakes is uneven and different in dimictic Heiligensee as compared with that in polymictic Müggelsee (Fig. 4). In Heiligensee, the bottom temperature increases much slower than the surface temperature and even reveals a slight cooling trend at the beginning of the modeled period (Table 3). This is an apparent result of the growing thermal stratification that prevents the heat transfer to the bottom of the lake. In its current polymictic

Table 3. Mean linear trends in the lake-averaged (T_m), mixed layer (T_s) and bottom (T_b) water temperatures of both lakes, calculated at three different time averaging periods.

Averaging period	Heiligensee			Müggelsee		
	T_m	T_s	T_b	T_m	T_s	T_b
1961–2002	0.0135	0.0207	–0.0070	0.0186	0.0196	0.0166
1961–2055	0.0194	0.0258	0.0059	0.0184	0.0204	0.0124
1961–2100	0.0294	0.0365	0.0130	0.0331	0.0346	0.0241

Fig. 5. Modeled seasonal course of the temperature averaged over the lake and over decades: (a) Heiligensee and (b) Müggelsee.



state, Müggelsee is regularly mixed down to the bottom with an equal surface and bottom temperature. In the future scenarios, the difference between the temperatures at the surface and at the bottom increases, which indicates a transition to the dimictic regime.

The seasonal pattern of changes in the lake-averaged temperature, T_m , does not always follow the same pattern as the air temperature changes described above. In both lakes, the spring (January to April) temperature during 1991–2000 is 0.5–1.0 °C higher as compared with that during 1961–1970, which agrees with the increase of the air temperature in winter (cf. Figs. 3a and 5, solid and long-dashed lines in both panels). However, the GLOWA scenario produces no significant mean temperature increase in Müggelsee (dash-dotted line in Fig. 5b). During the same period, the increase of the Heiligensee temperature is more pronounced (dash-dotted line of Fig. 5a) and it takes place mostly in the spring. The RCAO MPIB2 scenario predicts an appreciable increase in the mean temperature of both lakes that is distributed uniformly over the seasons (dotted lines in Fig. 5).

Thus, the response of the mean temperature to the increased heat input from the atmosphere is different in polymictic and dimictic conditions and is unevenly distributed in the seasonal cycle, which is apparently accounted for by the concurrent changes in the vertical temperature stratification. The simplest characteristic of the vertical stratification is the difference in the surface and bottom temperatures, $T_s - T_b$, whose seasonal course, when averaged over the same decades as before, allows the mixing regime transformations in both lakes to be traced (Fig. 6). The very low vertical temperature difference, which is typical of Müggelsee during 1991–2000,

is already replaced at the beginning of the 21st century (2021–2030) by the uninterrupted stratification period from April to September. This period exhibits a temperature difference of up to 5 °C across the water column that indicates a transition to the dimictic regime. In Heiligensee, the same period of 2021–2030 is characterized by a one-month increase in the duration of the summer stratification and by a shift of the winter stratification period from the late winter/early spring to the earlier winter dates. The end of the 21st century (2071–2080) is marked in both lakes by the disappearance of the winter stratification, which is only occasionally seen in the course of Müggelsee's temperature while completely disappearing in Heiligensee. Obviously, the water temperature no more falls below 4 °C and the mixing regime in both lakes becomes warm monomictic.

These alterations in the mixing regime of both lakes are responsible for the non-uniformity in the mean water temperature increase described above. Along with the lake-averaged temperature, the changes in the mixing regime strongly affect the vertical distribution of the additional heat input, which is revealed by the long-term changes in the mixed-layer temperature, T_s , and the bottom temperature, T_b (Fig. 7). As long as Müggelsee remains polymictic (Fig. 7a), both T_s and T_b follow the trends in the air temperature (solid line in all panels of Fig. 7). The only remarkable difference is that the increase in the air temperature during winter is followed by the time-biased increase of T_s in the late winter/early spring. The reason for the bias is the occasional ice cover and the low rate of vertical mixing in winter. In the first half of the 21st century (Fig. 7b) changes in T_s still echo the air temperature trends but the transition to the dimictic mixing regime results in a strong (more than 2 °C) decrease of T_b in summer; now, the

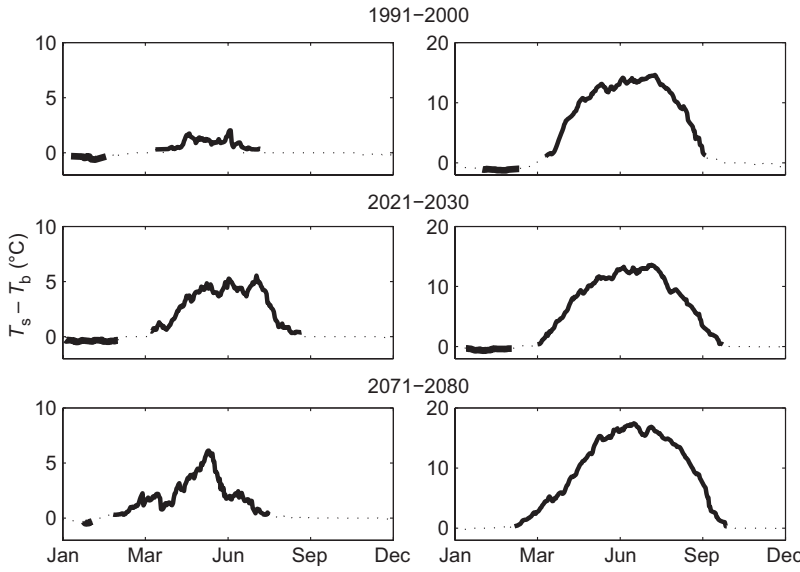


Fig. 6. Decadal mean seasonal courses of the surface and bottom temperature difference ($T_s - T_b$) in Müggelsee (left) and Heiligensee (right). Solid lines mark periods of stratification, dotted lines correspond to full mixing periods ($T_s = T_b$).

stratification prevents heat input from the surface. In addition, the transition to the warm monomictic regime at the end of the century (Fig. 7c) causes the 1–2 °C increase in T_b during summer. This increase is the consequence of the fact that the near-bottom water masses in summer do not form during the spring overturn (as in dimictic lakes) but remain at temperatures distinctly above 4 °C during the entire year. The temperature of Heiligensee follows the same pattern (Fig. 7) except for the fact that all of the changes take place earlier. The decrease of T_b expected in Müggelsee during the next 20–50 years is already observed in Heiligensee (Fig. 7d). Heiligensee has already changed to a warm monomictic lake in the first half of the 21st century with a corresponding increase in the near-bottom temperatures (Fig. 7e). Afterwards, it reveals typical monomictic behavior with a slight (less than 1 °C) decrease in the T_b during summer (on account of the strengthened stratification) and a simultaneous increase of both the T_s and T_b during the rest of the year (following the air temperature increase).

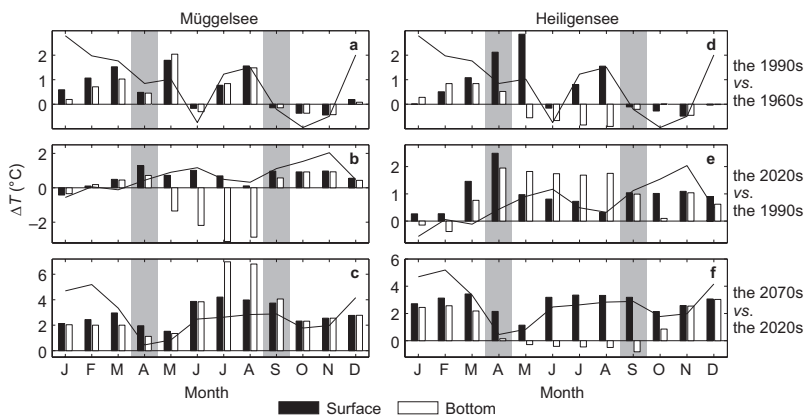
Discussion

The mean temperature increase of 0.3 °C per decade, which is predicted by the model in both lakes, is close to the trend in the local air temperature and suggests an annual mean equilibrium

in the lake-atmosphere heat exchange. Similar average warming rates of 0.25 to 0.30 °C per decade have been reported in other regional studies regarding the responses of lakes to climate change (Verburg *et al.* 2003, Arhonditsis *et al.* 2004, Danis *et al.* 2004). Other studies devoted to the alpine or tropical meromictic lakes reported lake temperature trends of only 0.10–0.15 °C per decade, which is also lower than the regional atmosphere warming (Livingstone 2003, Vollmer *et al.* 2005, Coats *et al.* 2006). This difference is apparently caused by the thermal inertia of the meromictic hypolimnion, which remains unmixed during several decades and does not respond to the atmospheric forcing.

In contrast to the lake mean temperature, the warming trends in the epilimnion and hypolimnion of a dimictic lake are different from that of a polymictic lake. If the latter undergoes nearly equal warming across the water column, the temperatures near the bottom in the former will remain nearly constant or reveal a slight tendency to decrease unless the lake switches to the monomictic regime. This behavior has been reported as a characteristic of dimictic lakes by e.g. Hondzo and Stefan (1993), De Stacio *et al.* (1996) and Danis *et al.* (2004). Danis *et al.* (2004) also drew a distinction between the absence of the hypolimnion warming in dimictic lakes and the appreciable near-bottom warming in the monomictic lakes. In the latter case,

Fig. 7. Relative changes in the lake temperatures averaged over monthly bins (bars). (a–c) Müggelsee, (d–f) Heiligensee. The corresponding change in the monthly mean air temperature is shown by the solid line in each panel. Shaded areas mark periods of spring and autumn overruns.



the warming of the deep layers is caused by the absence of the winter stratification rather than by the increased heat input in summer. In our results, this effect is demonstrated by a strong increase of the hypolimnion temperatures in Heiligensee during the transition from the dimictic to the warm monomictic regime. The predicted mixing regime transition sequence in both lakes is an important implication of the presented results and can be described by the following general temporal pattern.

Polymictic lakes

From the end of the 20th century until now: The mean, surface and bottom temperatures generally follow the trends in the air temperature. The winter air temperature increase is followed by the time-biased lake temperatures increase in the late winter/early spring (Fig. 7a).

First half of the 21st century: A transition from the polymictic to the dimictic regime occurs. Surface temperatures still echo the air temperature trends. Yet, the transition to another mixing regime results in a *strong decrease* in the bottom temperature during summer (Fig. 7b) because the summer stratification starts to prevent the heat input from the surface. As a result, the mean lake temperature remains nearly unchanged in summer (cf. Fig. 5b) in spite of the increased heat input from the atmosphere.

Second half of the 21st century: A transition from the dimictic to the warm monomictic regime occurs. The main feature of this transition is the *strong increase* in the summer bottom

temperature, whose formation takes place from this moment during the mild winters and not at the 4 °C spring overturn. It is worth noting that this abrupt increase in the decadal mean temperatures (Fig. 7c) will very probably reveal itself in annual scales as “sawtooth”-like rather than as a gradual temperature increase as long as the warm monomictic regime is interleaved by an occasional dimixis appearance in relatively cold years (Livingstone 2003).

Dimictic lakes

From the end of the 20th century up till now: The trends in the surface temperature are similar to those in polymictic lakes. The distinctive feature of dimictic lakes is the decrease in the bottom temperature despite the increase in the air temperatures (Fig. 7d). Therefore, the mean temperature either does not increase or even reveals a slightly negative trend (cf. Fig. 5a).

First half of the 21st century: A transition from the dimictic to the warm monomictic regime occurs with a corresponding increase in the bottom temperature during the summer (Fig. 7e).

Second half of the 21st century: The warm monomictic regime is dominant. The surface temperature follows the air temperature in winter as well as summer. The bottom temperature increases appreciably in winter with minor variations in summer (Fig. 7f).

Thus, both lake types undergo the same mixing-regime transformation pattern but in dimictic lakes, all transitions appear several decades earlier.

One of the most important consequences of these mixing regime transitions for lake ecology is the abrupt change of the near-bottom temperatures and the mixing regime during summer. The polymictic/dimictic transition suggests development of a summer stratification followed by a 1–2 °C drop in the bottom temperatures during summer. Ceasing of near-bottom mixing is known to threaten the lake because of the development of the hypolimnion hypoxia (Golosov *et al.* 2008), which can trigger the release of iron-bound phosphorus from the sediment. The concurrent temperature drop can, however, significantly affect the microbial activity in the sediment and slow down the biochemical processes (Madigan *et al.* 2000). The colder hypolimnion can also negatively affect the benthic and fish communities. The next step in the mixing regime transformation is the transition to the warm monomictic state which is accompanied by an abrupt increase in the bottom temperatures during summer. When superimposed with the strong summer stratification, this increase can drastically accelerate the deep oxygen depletion and, as a result, the internal phosphorus load.

For various lakes located in the same region and undergoing the same atmospheric forcing, the lake depth is the main factor that determines the seasonal mixing regime; although, such factors as wind exposure, river inflow and water transparency can also contribute. The transparency of the water is especially important for the mixing regime because as soon as it widely varies between lakes, it can significantly affect the stability of the water column (Mazumder and Taylor 1994, De Stasio *et al.* 1996). For the period of 1961–2100, model scenarios with the same external forcing as before but with variable mean depths and extinction coefficients can provide an estimate for the mixing regime transition time in various lakes of the region. A series of such model runs is performed for lake depths ranging from 1 to 100 m with typical extinction coefficient values between 0.5 and 2.5 m⁻¹, which roughly correspond to the Secchi depths between 3.4 and 0.7 m. A summer stratification duration of 120 days or longer is chosen as a criterion for the polymictic/dimictic transition. If, in addition, the temperature in the lake never drops below 4 °C, then the lake is assumed to be

warm monomictic. According to the calculations of the model, lakes with depths between 40 and 50 m should have already undergone a transition from the dimictic to the warm monomictic regime (Fig. 8). Since all of the lakes in the Berlin-Brandenburg region are shallower, there is no way to verify this result using observational data. The scenarios suggest that at the end of the century the winter stratification will completely disappear in the majority of lakes in the region (cf. years 2080 to 2100 in Fig. 8). The transition of polymictic lakes to the dimictic regime is predicted in a much narrower range of lake depths, which correspond, however, to a large number of shallow lakes. In contrast to the dimictic/monomictic transition, water transparency plays an important role in this case. Figure 8 demonstrates that a decrease in water transparency accelerates the transition to the dimictic regime. Hence, any long-term prediction of the mixing regime in shallow lakes (i.e., in those with a depth comparable to the Secchi depth) remains uncertain without a future water quality scenario.

The future projections that have been presented above are based on one of the most “optimistic” IPCC SRES emission scenarios, B2 (Nakićenović and Swart 2000). The aim of the presented work is to estimate the *qualitative* change in the mixing regime of shallow temperate lakes in response to an increased heat input from the atmosphere. Therefore, a comparison of different emission scenarios, various global climate models and regional downscaling methods is out of the scope of this study. Generally, a stronger global warming trend would result in the same sequence of mixing regime transitions, as outlined above, taking place earlier in time. Hence, one can conclude that towards the end of the century the majority of lakes that are deeper than 10 m will change their mixing regime to warm monomictic (Fig. 8) with any future scenario of global warming. The fate of very shallow lakes, in turn, depends strongly on the water quality and cannot be estimated a priori from warming scenarios only.

Conclusions

The present study demonstrates the changes in

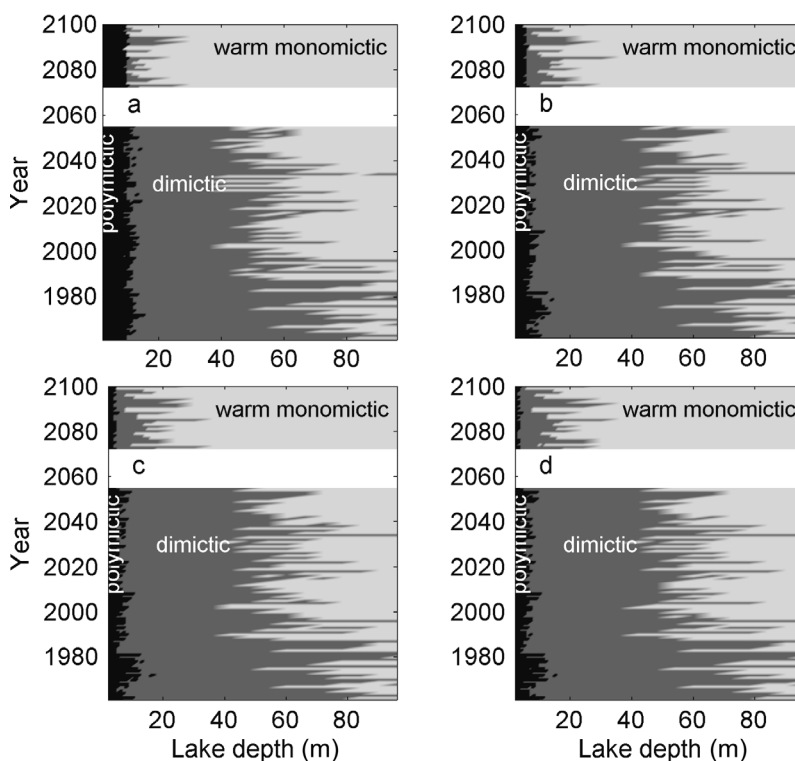


Fig. 8. Scenarios of the seasonal mixing regime transition for lakes of different depths and water transparencies in north-eastern Germany. **a–d:** extinction coefficients of 0.5, 1.0, 1.5 and 2.5 m^{-1} , respectively.

the temperature and mixing regime that are currently occurring in the small lakes of temperate regions. The future projections suggest an abrupt alteration in the seasonal mixing regime in the majority of the lakes, which warns of far-reaching ecological consequences. The most important results of this study can be summarized as follows:

- The year-round temperatures in two small German lakes follow the local-air warming trend. The result can likely be extrapolated to the majority of poly-, di-, and monomictic lakes located in temperate and boreal regions. The equilibrium of the heat with the atmosphere is apparently inherent for lakes mixed at least once per year and distinguishes them from alpine and tropical meromictic lakes, which reveal significant inertia in response to climatic warming.
- The strongest increase in the lake-averaged water temperature takes place in winter and early spring, which is in agreement with winter warming that is observed in the local air temperatures.
- The future scenarios suggest an even stronger winter warming that is conditioned by the transition to the warm monomictic regime and as a result, more intense heat exchange with the atmosphere in winter.
- A series of mixing regime transitions in lakes are predicted to take place during future decades. The polymictic lakes will turn to dimictic around the mid-century and proceed to warm monomictic in 2100. In dimictic lakes, the transition to the warm monomictic state appears even earlier.
- Apart from terminating the vertical turbulent transport, the mixing regime transitions are followed by an abrupt change in the temperature conditions of the summer hypolimnion that is signified by a temperature drop during the polymictic–dimictic transition and a temperature rise of several degrees during the dimictic–monomictic transition. Combined with other factors, these changes can alter the conditions at the water–sediment boundary and significantly affect the ecological state of the lakes.
- The timing of the envisaged mixing regime

transition from dimictic to warm monomictic in different lakes strongly depends on the lake depth. In turn, the mixing conditions in the polymictic lakes are more sensitive to water transparency than to the mean lake depth.

The latter result has an important implication for the understanding of the response of shallow lakes to global warming. Transparency can vary concurrently with the external atmospheric forcing depending on the changes in the trophic state of the lake. Thus, biological production can provide feedback to the physical processes by accelerating the changes in the seasonal mixing regime or by playing a self-regulating role (e.g., decreased vertical mixing can provoke higher plankton mortality or lower production, which in turn results in a transparency increase and re-establishment of mixing). This backward effect of lake biology on the thermal regime should be taken into account in future scenarios of lake functioning.

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